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The objective of this research project was to establish a better understanding of in-well and cross-well carrier transport in multiple quantum well (MQW) semiconductors. Carrier emission from both multiple and single quantum well devices have been studied in detail in p-i-n doped MQW SEED-type modulator structures and in waveguides. Simultaneous measurements of electron and hole emission rates has been accomplished for the first time leading to important conclusions concerning thermionic emission models for quantum wells. Extensive modeling of the dynamical optical response relating to cross-well carrier transport has been carried out. Spin relaxation has also been used successfully to monitor carrier dynamics in MQW devices. A new family of mode-locked lasers have been developed for time resolved measurements which are looking extremely attractive as ultrashort pulse sources for GaAs-based optoelectronic devices.

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Foreword

The objective of this research project was to establish a better understanding of in-well and cross-well carrier transport in multiple quantum well (MQW) semiconductors. Cross-well transport is important in establishing the fundamental operating characteristics of a number of important new MQW devices such as photodetectors, modulators, logic devices, waveguide switches and lasers relevant to present and future electronic and optoelectronic systems. The role of charge transfer by tunneling, thermionic emission and diffusion in strained and unstrained MQWs has been investigated by time resolved laser techniques and computer modeling. Carrier emission from both multiple and single quantum well devices have been studied in detail in p-i-n doped MQW SEED-type modulator structures and in waveguides. Simultaneous measurements of electron and hole emission rates has been accomplished for the first time leading to important conclusions concerning thermionic emission models for quantum wells. Extensive modeling of the dynamical optical response relating to cross-well carrier transport has been carried out. Spin-relaxation has also been used successfully to monitor carrier dynamics in MQW devices. This has lead to a unique method of distinguishing the effects of phase space filling and Coulomb screening on excitonic saturation. As an additional spin-off from this research a new family of mode-locked lasers have been developed for time resolved measurements which are looking extremely attractive as ultrashort pulse sources for GaAs-based optoelectronic devices.

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1. Statement of Problem Studied

The operating characteristics of most new electronic and optoelectronic devices based on semiconductor quantum well technology, (such as MQW photodetectors, lasers, SEED logic devices, optical modulators and resonant tunneling devices), depend on transport of electrons and holes transversely to the layers. However, cross-well transport is presently not well understood. Processes such as thermionic emission, tunneling and trapping can effect the efficiency of these devices, and ultimately, the fundamental upper limits on speed. It is therefore very important to characterize, and especially time resolve these processes to allow design criterea for high speed devices to be established. The situation may be contrasted to bulk semiconductors in which no equivalent mechanisms exist.

The method chosen to study these fundamental processes is the time resolved laser pump-probe technique. By employing band gap resonant optical nonlinearities, spatial carrier dynamics can be monitored with sub-picosecond resolution. This research has concentrated on two materials systems, lattice matched GaAs/AlGaAs quantum wells and the strained InGaAs/GaAs system. The former has been studied by using a commercial synchronously pumped dye laser producing 1ps pulses in the 830 - 860nm range while the latter was studied in the 950 - 980nm range using a home-made, mode-locked Ti:sapphire laser producing sub-100fs pulses. Important conclusions are drawn on the role of resonant tunneling, thermionic emission and trapping in this report.

As part of this project we have also developed an entirely new range of sub-100fs $Cr:LiSrAlF_6$, $Cr:LiCaAlF_6$ and $Cr:LiSrCaAlF_6$ lasers which are pumped by a krypton laser and look set to revolutionize the ultrashort pulse area by offering diode pumped ultrashort pulse, tunable lasers within the next few years.

2. Summary of Most Important Results

Both experimental measurements and modeling studies have been carried out on this project. The experimental studies have consisted of time resolved pump-probe measurements in p-i-n modulator structures whereby the light passes transversely to the MQW layers, and in waveguides in which the light travels parallel to the layers. The waveguide geometry has allowed single wells to be employed which allowed a considerable simplification of the interpretation of carrier emission mechanisms and rates from quantum wells.

2.1 Cross-Well Transport in GaAs/AlGaAs MQW p-i-n Doped Structures

Several experimental techniques have been used to study charge transfer in MQWs in applied electric fields, including electrical measurements, photoluminescence and excite-probe techniques. The latter method[1-6] offers the advantage of time resolution and convenience for the study of SEED-type structures, in which high electric fields in excess of 10^5 V/cm can be applied by a reverse bias of only a few volts. A number of papers have reported low excitation level measurements in which resonant tunneling is clearly resolved.

At higher excitation levels appropriate to the operating conditions of SEED and other nonlinear optical switching devices, absorption saturation and space-charge build-up can become significant. The effects of absorption saturation in electrically biased MQWs have been studied under steady state conditions by Wood et al[7] and Fox et al[8,9]. Here we report time resolved measurements under these higher excitation conditions more closely related to device conditions.

The MOVPE grown p(i-MQW)n sample used in these studies consisted of an intrinsic region ~1μm thick comprising 87Å wide GaAs wells and 60Å wide $Al_xGa_{1-x}As$ (x=0.3) barriers. The substrate was removed by selective etching and the sample mounted on a sapphire substrate. A ~200μm window on the p-side allowed light to pass perpendicular to the wells. An external d.c.

reverse bias electric field was applied across the QW layers via contacts made to the doped regions. Transmission spectra of the sample at three different applied voltages are shown in figure 1. (Some additional modulation in transmission at longer wavelengths is caused by Fabry-Perot effects). With increasing reverse bias voltage, the whole band edge transmission shifts to longer wavelengths, with the exciton valleys remaining resolved.A mode-locked and cavity dumped styryl 9 dye laser (Coherent 702), synchronously pumped by a mode-locked, frequency doubled Nd:YAG laser (Coherent Antares) produced ~1 psec pulses tunable between 820 and 870nm. A conventional pump-probe arrangement was employed with both beams focussed onto the sample by a single 10cm focal length anti-reflection coated lens. Both beams had ~35μm (FW1/e^2M) spot sizes on the sample. Cavity dumping reduced the repetition frequency to 7.6MHz thus avoiding pulse-to-pulse charge accumulation since the carrier recombination time is on the order of 10 nanoseconds. The pump beam was mechanically chopped at 1kHz and the probe signal monitored using phase sensitive detection. Changing the external circuitry had no effect on the measured transients, i.e. the transmission changes occurred on timescales shorter than the bias circuit response time.

Transmission changes measured as a function of probe delay are shown in figure 2 for several reverse bias voltages under conditions of relatively low excitation level (8pJ per pump pulse producing on the order of $5x10^{10}cm^{-2}$ electron hole pairs). The d.c. bias causes a red shift of the absorption edge via the quantum confined Stark effect (QCSE). The laser was tuned to the long wavelength side of the exciton resonance and measurements made at the wavelength corresponding to the maximum transmission change for each applied voltage. The rise in signal, $\Delta T(t)$, results from the blue shift of the exciton as the photogenerated electrons and holes leave the wells and move towards opposite doped regions. The charge separation screens the applied field and hence reduces the exciton shift produced by the QCSE. The rise time of the signal therefore gives a measure of the rate that the carriers escape from the quantum wells to establish a photocurrent. The subsequent

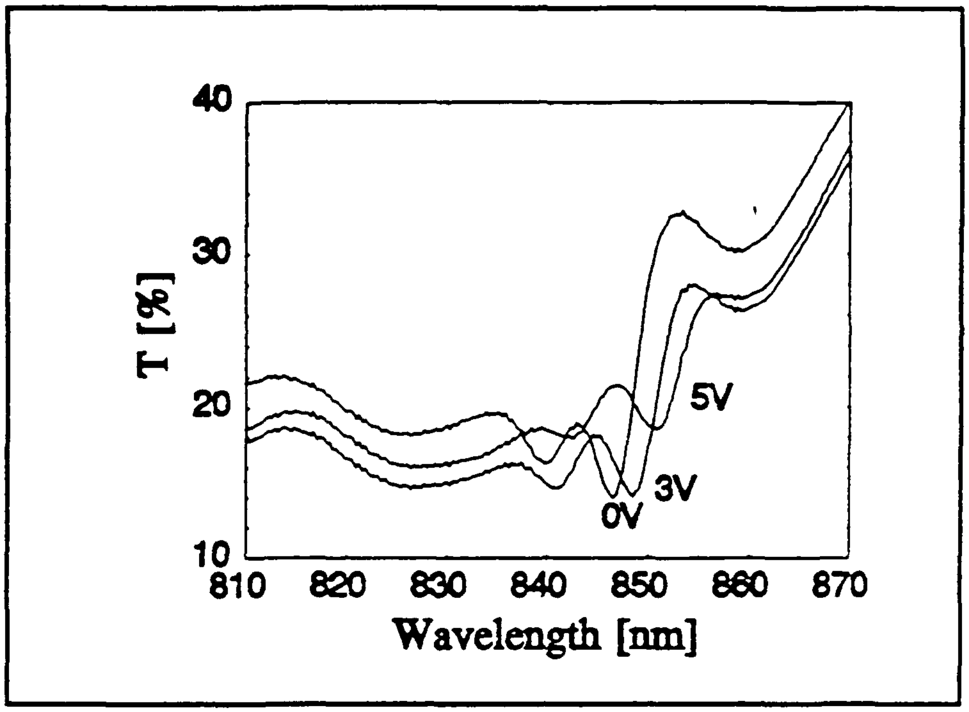

Figure 1 Transmission spectra of MQW modulator under three different bias conditions.

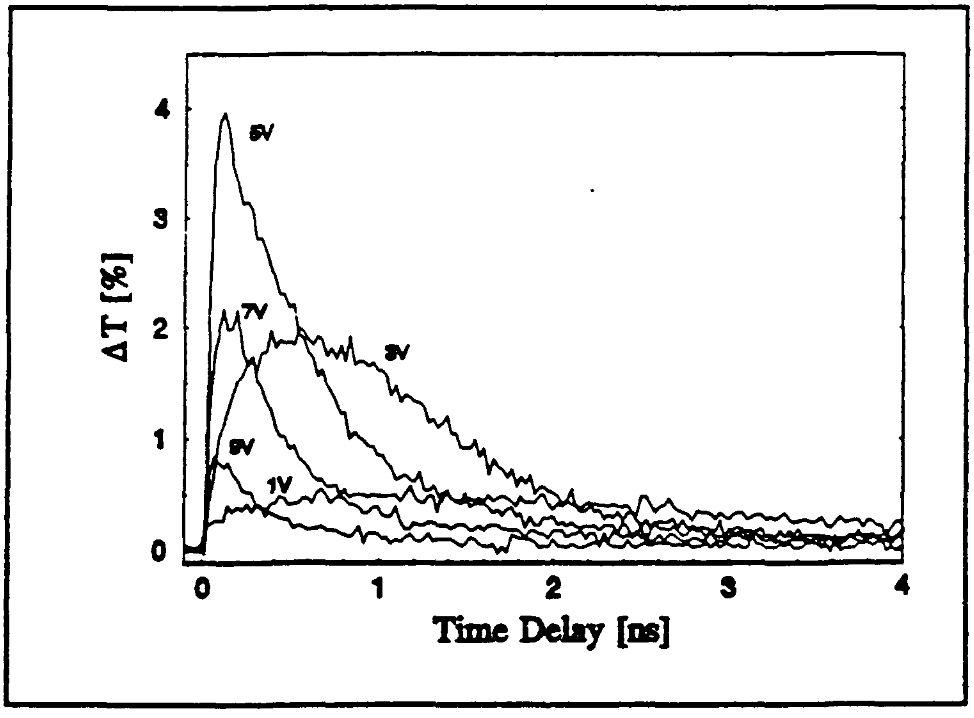

Figure 2 Pump-probe measurements at different reverse bias voltages (63µW average power at 7.6MHz).

fall in signal is caused by transverse diffusive conduction in the doped regions thus restoring the original field. The data was fitted to rising and falling exponential functions to determine risetimes, t_r, and decay times, t_d.

$$\Delta T(t) = \Delta T_{max} \; [1 - \exp(-t/t_r)] \; \exp(-t/t_d)$$

These processes all take place on timescales significantly shorter than the carrier recombination time and the response time of the external circuit.

The signal rise times, t_r are plotted in figure 3 as a function of d.c. bias. At low voltages, when the escape of electrons from the wells is dominated by thermionic emission, the rise time is around 500ps. Above 2.5 volts, the rise time decreases and gives a minimum of around 20ps at 5volts. This reduction is due to the addition of tunneling to the emission process. The minimum

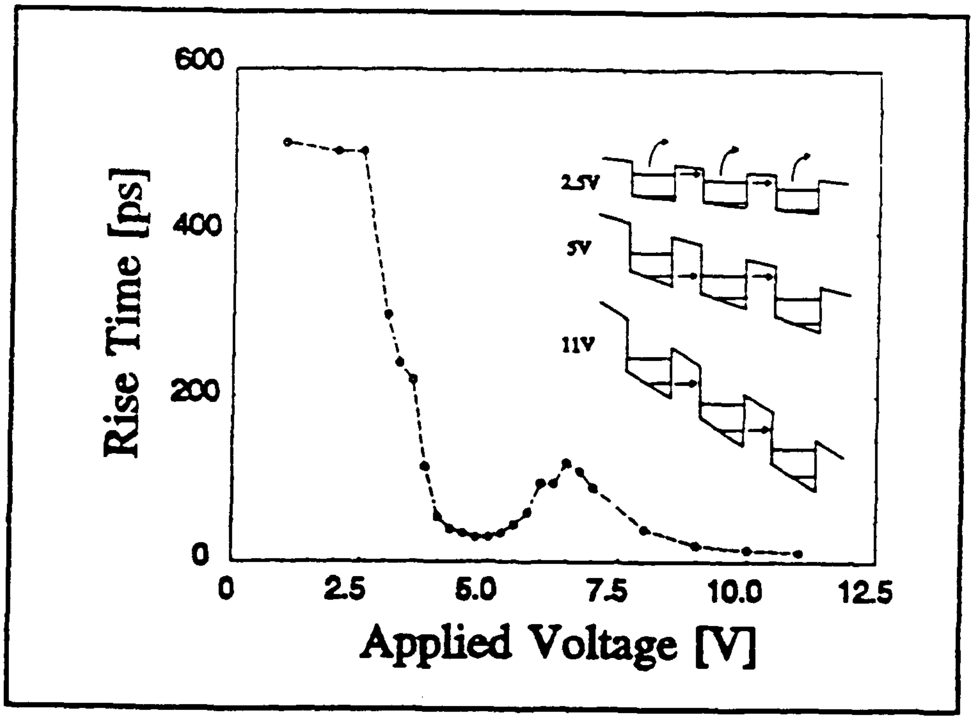

Figure 3 Photoconductive rise time of a MQW pin modulator displaying resonant tunneling at an applied voltage of 5V.

value occurs under conditions of resonance between the n=1 level of one well and the n=2 level of the adjacent well. For voltages above resonance, the rise time increases to ~130ps before falling again when tunneling is possible from the n=1 level directly into the continuum. Above 10 volts this time constant reduces to the transit time for carriers across the 1 μm wide intrinsic region. The largest signal is measured on resonance at 5V when the carriers are rapidly ejected from the wells allowing a larger density to accumulate in the doped regions. At high fields, the magnitude of the signal is reduced due to broadening of the exciton feature thus decreasing the maximum transmission change.

Transmission changes as a function of delay time, $\Delta T(t)$, are shown in figure 4 at larger pump powers for three different applied voltages. The voltages chosen are, (a) 3V, below resonant tunneling conditions, (b) 5V, on resonance, and (c) 7V, above resonance. At the higher pump levels, the time dependence of the transmission is much more complex. For instance, at 5 volts, a transmission change as large as 30% was recorded with two time constants evident in the rising edge, while the time scale for the decay of the signal increases and is no longer a simple exponential. The initial fast rise in transmission and the large total transmission change is consistent with exciton absorption saturation at carrier densities in excess of $10^{11}cm^{-2}$. The slower component of the rise can be attributed to screening of the d.c. field and the corresponding blue shift as observed for low excitation. At higher excitation levels, the large generated carrier densities result in an appreciable cancellation of the applied field. The consequences of this are observed more clearly in the signal decay rather than the rise. We do not expect the transverse diffusion process to be density dependent. Thus, we interpret the slower recovery at high carrier densities as a reduction in the emission rate for the carriers from the quantum wells when the field is effectively screened by the space charge. The carrier escape rate therefore limits the decay rate of the signal. A reduced local field corresponds to a shift to the left for the conditions plotted in figure 3. In the case of a d.c. bias

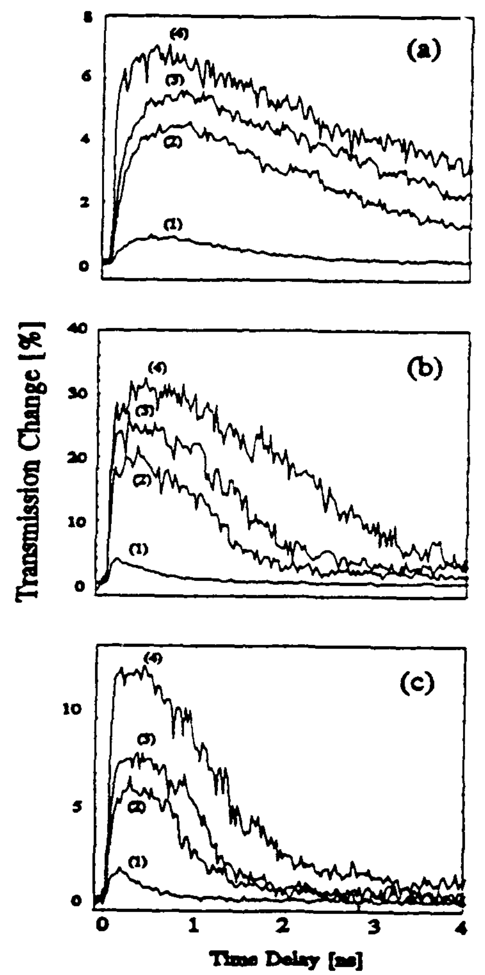

Figure 4 Pump-probe measurements at three different voltages, (a) 3V, (b) 5V and (c) 7V, and average pump power levels, (1) 63μW, (2) 0.63mW, (3) 1.0mW and (4) 2mW.

of 5 volts, when the initial carrier escape time constant is on the order of 20psec, the carrier emission time may slow by over an order of magnitude as the screening reduces the local fields. At 3 volts, the difference in decay time at high excitation levels is not so evident because the initial conditions give a slower carrier emission rate. On the other hand, at 7 volts the high excitation results again give a slower recovery than at low level, however the overall recovery is faster than for the 5 volt

case since screening moves the device through resonant tunneling conditions.

We have thus identified the consequences of screening of the applied electric field at high photogenerated carrier densities in a MQW SEED device by space-charge build-up on picosecond timescales. In a device which shows a 20psec time constant for the establishment of the photocurrent under conditions of resonant tunneling, for a laser spot diameter of ~35μm, the recovery time was found to increase to several nanoseconds at carrier excitation levels above 10^{11}cm^{-2}.

2.2 Cross-Well Transport in InGaAs/AlAs MQW p-i-n Doped Structures

Similar experiments have been carried out in InGaAs/AlAs MQW p-i-n doped modulator structures. A home-made, sub-100fsec Ti:sapphire laser pumped by a cw argon-ion laser was employed. The modulators were grown at the University of London Advanced Semiconductor Interdisciplinary Research Centre and supplied by Professor Gareth Parry of University College London. These samples have extremely high barriers for both electrons and holes so that we would

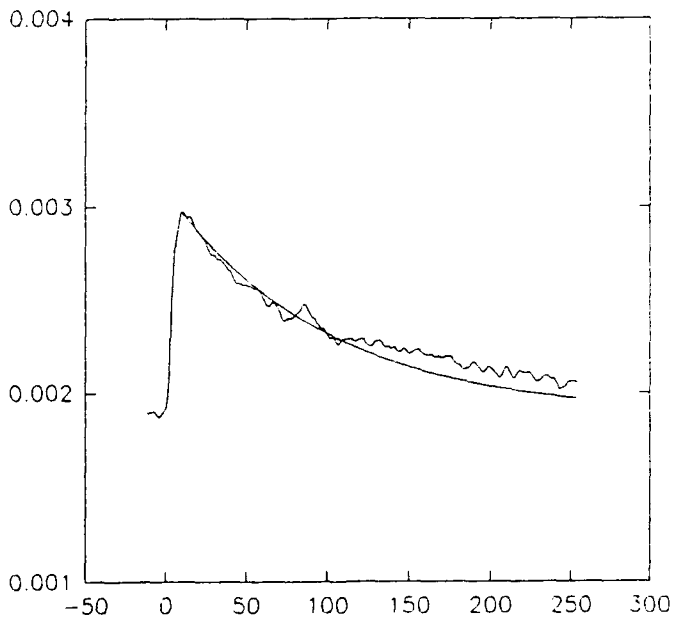

Figure 5 Time resolved pump-probe measurements of p-i-n doped InGaAs/AlAs modulator.

expect relatively slow carrier emission rates (on the order of nanoseconds). However these samples gave a significanlty shorter time constant on the order of 100psec which was insensitive to field or temperature, figure 5. Our conclusion was that traps in the AlAs barriers cause recombination of the carriers and therefore recovery of the electroabsorption signal. Future studies will address samples with lower, GaAs and AlGaAs barriers and determine the effects of strain on the cross-well carrier dynamics.

2.3 Modeling of cross-well carrier transport in MQW p-i-n structures

A self-consistent time and spatially resolved model was developed to explain the nature of cross-well transport in MQW devices. The model is solved numerically to obtain a fit to experimental excite-probe data to give details of the changes in local dynamical changes in field and the rate that optically excited carriers are swept out of the quantum wells.

In the experiments described above, ultrashort pulses generate excitons, which rapidly thermalize (within a few hundred femtoseconds) to form a population of electrons and holes within the quantum wells. The charge separation as the carriers escape from the wells and drift to their respective contact regions, results in a change in the local electric field in the quantum well region which can be described using Gauss' Law. In fact, the applied electric field across the device is being reduced by the screening effect of these carriers. It is this local field change which detunes the exciton through the QCSE and leads to a change in transmission for the delayed probe pulse. Thus, the rise time of the transmission change is a direct measure of the time for the carriers to escape from the wells and start moving towards the electrodes. The phenomenalogical model we use to calculate the transient response uses various time constants for the different processes that can affect the photogenerated electrons and holes. A schematic of these processes is shown in figure 6.

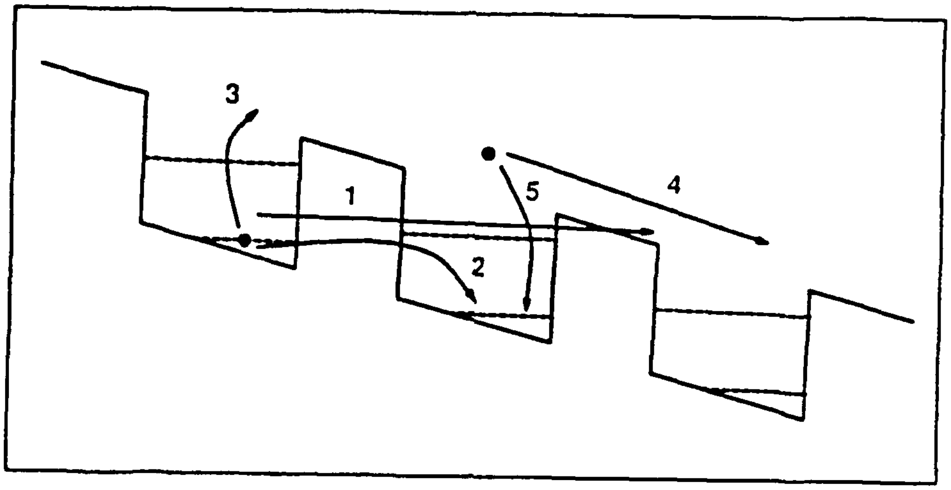

Figure 6 Dynamic representation of the various time constants involved in the cross-well transport of carriers.

A time constant is attributed to each process.

1) *Tunneling from a quantum well bound state into the continuum.* This field dependent time constant was calculated from the width of the tunneling resonance obtained by solving the Schrödinger equation for the simplified case of two wells in an electric field[10]. The tunneling time shows a marked decrease when the electric field is of such a value that the n=1 electron energy level in one well is coincident with the n=2 electron energy level in the adjacent well. This resonant tunneling condition also manifests itself strongly in the rise time of the experimental characteristics. At this resonance, the single well wavefunctions experience mixing in such a fashion that non-crossing of the single particle energies is observed.

2) *Scattering between bound states in adjacent wells.* For low excite powers (low carrier densities) it is assumed that this process is insignificant compared to the tunneling escape process described above for our sample and is neglected in the present calculation. However at higher carrier population levels this process should become more important as carrier-carrier scattering rates increase.

3) *Thermionic emission from a quantum well bound state into the continuum.* A field dependent time constant for thermionic emission in biased quantum wells similar to Fox et al[11] was employed.

4) *Drift of free carriers in an electric field.* A field dependent time constant was obtained using the saturation drift velocity. It is anticipated that the mobility values used here will be far smaller than those for regular GaAs as (i) the mobile carriers will be at energies well above the band gap in the GaAs band structure and hence have a much larger effective mass and (ii) motion is through a non uniform material as both wells and barriers are being traversed. Electron and hole mobilities of 150 and 20 $cm^2V^{-1}s^{-1}$ respectively were used in the calculations.

5) *Capture of free carriers into bound states.* Room temperature measurements indicate capture to be on the order or less than 1 picosecond[12]. Furthermore, in bulk GaAs the mean free time between collisions for an electron is about 0.3ps which is not anticipated to change by orders of magnitude in a quantum well material. In this calculation, the capture time is set to a constant value, for both electrons and holes.

The transient response is solved self-consistently by including the space-charge effects of the electron and hole populations, i.e. the change in the local electric field in the structure is calculated using Gauss' Law for a plane parallel capacitor. Each well was approximated by a plane of charge corresponding to the difference in hole and electron populations at that instant. Previous calculations for these experiments have ignored space-charge effects. These effects will become more important at higher carrier densities as the change in the local electric field can become comparable to the applied electric field, thus leading to the inhibition of motion of the carriers towards the doped regions. A set of coupled differential equations describe the bound and free electron and hole populations in the sixty quantum wells of the device. An additional two partial differential equations describe the accumulation of photo-generated charge in the doped layers.

Experimental pump-probe measurements show that the transient signal decays on a timescale

of a few hundred picoseconds at low excitation levels. This time scale is much faster than the external circuit can respond and is also significantly faster than the carrier recombination. Ambipolar carrier diffusion along the wells[2] would give a timescale of around 25ns for a Gaussian distribution of charge of the same dimensions as the laser spot size. The relaxation can only be caused by electron diffusion within the n-doped layer. A simple estimate based on the electronic diffusion coefficient is still too slow. Livescu et al[6] proposed a "diffusive conduction" mechanism which accounted for the rapid washing out of the field by an electromagnetic propagation in the highly doped regions and was modeled by a two dimensional resistance-capacitance network. In our microscopic model, the transverse dynamics of the donor electrons in the n-type electrode are included physically. These electrons will move to compensate for the motion and separation of the Gaussian transverse distributions of electrons and holes which reflect the laser beam profile. It is the transverse variation in the field which drives the transverse motion of the electrons in the n-doped region to wash out the induced voltage. Thus, compensation for the local fields can begin before the photogenerated charge reaches the doped regions. The mathematical formulation involves the Debye screening length and surface capacitance.

An additional effect which is included in the present model is to include the effects of a nonuniform field throughout the sample due to impurities (background doping) in the quantum well layers. The change in electric field in the intrinsic region of the device due to an assumed homogeneous density of impurities is calculated by Gauss' Law. The nonuniformity in electric field across the structure due to background doping is estimated at $\sim 20\mathrm{kVcm}^{-1}$.

The coupled system of partial differential equations (243 for our system) are solved by the Runge-Kutta method with a step-size of 20fs. The program allows access to the temporal and spatial evolution of the photogenerated populations. An example of this is shown in fig. 7. It can be seen that for 5V reverse bias, the nonuniformity of the electric field results in the electrons nearer to the

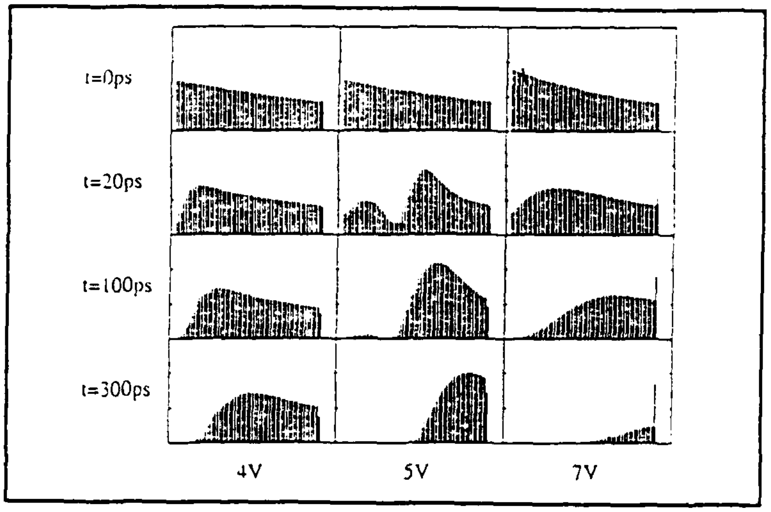

Figure 7 Representation of the electron densities in the quantum wells at various times and applied reverse biases.

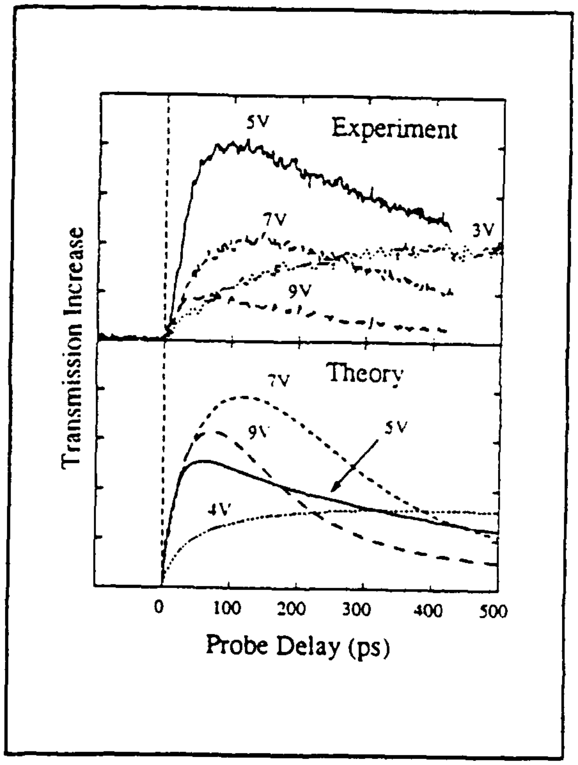

Figure 8 A comparison of (a) experimental and (b) theoretical transient transmission changes as a function of probe delay for different applied voltages.

p-region to be tuned to the tunneling resonance and as a result these carriers rapidly escape from the wells. The electrons closer to the n-region take somewhat longer to escape from the wells.

The change in the transmission is determined from the internal electric fields by comparison with experimental data for the device transmission as a function of reverse bias voltage under cw conditions for the various laser wavelengths used in the experiments. We can thus plot a direct comparison of the transmission change versus delay between experiment and the present numerical model, fig. 8.

From the transient transmission response in fig. 8 we can use the rising and decaying exponential fit as was done for the experiment to extract the rise and decay times of the response. These are shown in fig. 9. Rise times are in general agreement with experiment with the resonant

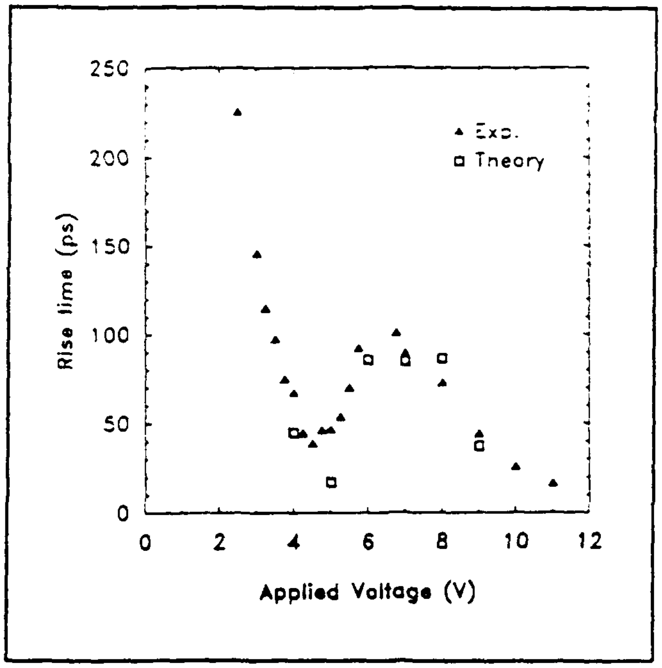

Figure 9 Comparison of the rise times for the theoretical and experimental responses from fig. 8.

tunneling at 5V clearly shown. The shape of the transient decay is actually determined by the form of the rising signal. Indeed the relaxation is not to the situation where all of the electrons and holes

reach the contacts but rather to an equilibrium situation where the transverse transport of the photo-generated carriers is at a slow enough rate that the transverse diffusion of the doping electrons can effectively instantaneously compensate for voltage changes. This can be seen in fig. 7 where even at 300ps a large number of the photo-generated electrons are still bound in the quantum wells yet the transient response is decaying. This may also answer the question of what happens to the holes.

Holes will take far longer, on average, to reach the p-type layer as tunneling is at a far lower rate for the larger effective mass in comparison to the electrons reaching the n-type layer. Thus, even when the transient response has completely disappeared, many holes will still be bound in the quantum wells, but resulting voltage changes within the structure will be compensated for by the doping electrons.

2.4 Measurements of Carrier Emission Rates in MQW waveguides

It has been proposed for some time that all-optical switching devices making use of band gap resonant optical nonlinearities could be speeded up by sweeping out the carriers in an electric field. Using a zero gap waveguide directional coupler[3,17] we have demonstrated that this is indeed the case for band gap resonant nonlinear refraction. The geometry used in the MQW waveguide was such that the sweep-out involved cross-well transport similar to that discussed above. By time resolving the nonlinear switching mechanisms this provides another method of monitoring the dynamics of cross-well transport.

The MQW structure studied in this work was MOCVD grown and consisted of an undoped core guiding region that contained 25 GaAs quantum wells each 100Å thick and separated by 100Å thick $Ga_{0.75}Al_{0.25}As$ barrier layers. The top (p-doped) and bottom (n-doped) $Ga_{0.75}Al_{0.25}As$ cladding layers regions were 1 and 3μm thick respectively. A ridge 4μm wide was produced in the top cladding by reactive ion etching and the device cleaved to a length of 500μm. Through effective

index loading, the MQW layer underneath the ridge confined light both in the vertical and lateral directions. The structure which is single moded in the vertical direction could support two lowest lateral modes to propagate simultaneously and beat with each other. The beating of these modes results in directional coupler-like action of the device.

The switch response time was measured using a picosecond optical pump-probe technique similar to that described above, however in this case, the two beams passed through the device co-linearly. In order to distinguish the two beams at the output, the polarization of the pump beam was rotated before being recombined with the time delayed probe and focussed at the input facet of the waveguide. The pump beam excited the TE modes of the waveguide while the probe beam excited the TM modes. A cross-polarizer placed after the output collecting lens, ensured that only the TM-polarized probe beam was monitored. The laser wavelength was set to 860nm where the absorption coefficient was estimated to be around $20cm^{-1}$. A d.c. power supply and a $1k\Omega$ series resistor were connected across the top and bottom contacts such as to reverse bias the diode.

By moving the probe delay stage such that the probe pulses arrived either before or after the corresponding pump pulses, directional switching of the probe due to the pump was observed. The on-off ratio was optimized in two stages. First the wavelength of the laser was adjusted for maximum contrast between the two output positions in the off-state (no pump beam). The amplitude of the synchronized pump pulses was then adjusted for the best switch-over response of the probe pulses arriving just before and after the pump pulses, figure 10.

The switch temporal response was obtained by varying the probe delay relative to the pump pulses. The switch-up time was limited by the pulse width of the laser. The recovery was found to depend on applied reverse bias voltage as shown in figure 11. The recovery time constant decreased from 500ps under no external bias down to 130ps with a reverse bias of 5V (corresponding to $100kVcm^{-1}$) applied across the device. Our previous measurements in an exactly similar but

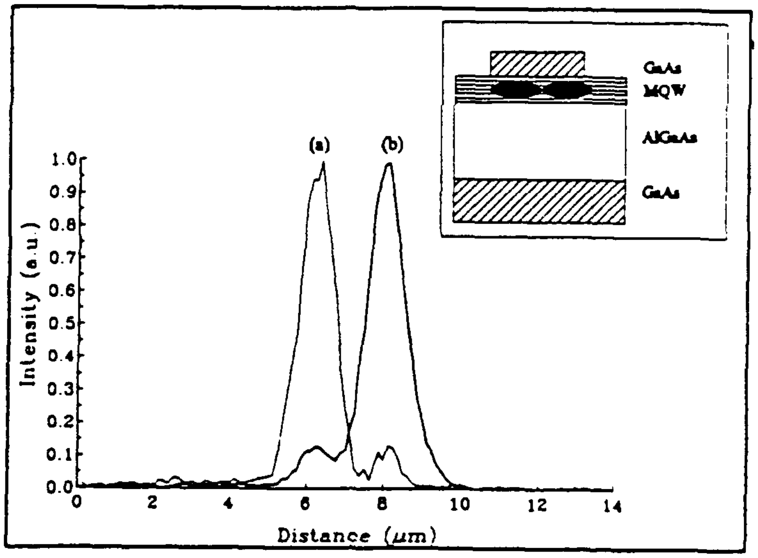

Figure 10 TV line scans of the near-field probe output signal from the zero-gap directional coupler.

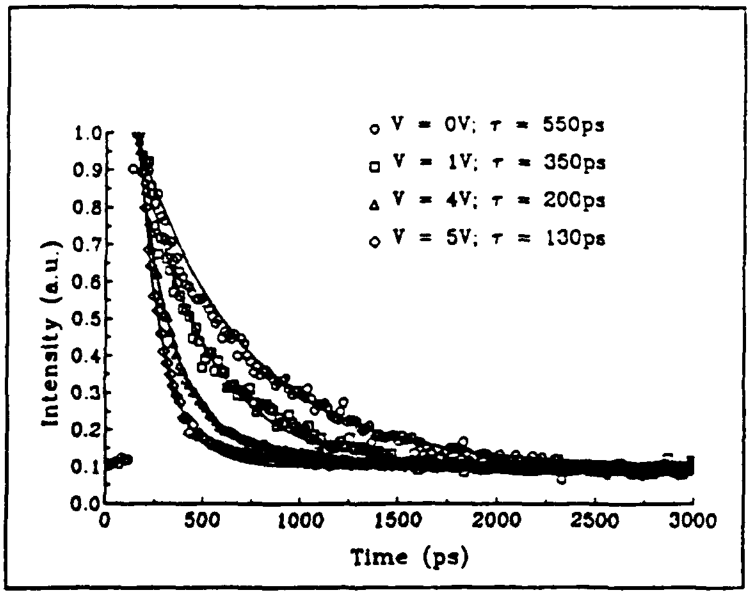

Figure 11 Recovery of the switched probe signal for different applied voltages.

undoped MQW directional coupler gave a 1.5ns recovery due to ambipolar diffusion of the carriers along the wells and out of the waveguiding regions[14]. The faster recovery of 550ps observed here under the unbiased condition may be due to the built-in field of the p-i-n structure.

From the observed fast switch-up time (laser pulse-width limited), we can deduce that the refractive nonlinearity responsible for the switch is mainly due to absorption saturation (band filling and exciton saturation) rather than the QCSE which would have a time constant associated with it similar to the time resolved results obtained in SEED devices as described above. The dynamics of the device are thus determined by the carrier generation rate for switch-on, and cross-well sweep-out of carriers into the cladding region for the recovery. The recovery rate is determined by the same cross-well transport mechanism as the SEED device. At low fields, the emission is primarily thermionic. As the field is increased, tunneling increases the sweep-out rate. In this device, the wavelength tuning of the laser restricted testing the device at higher applied fields as the exciton shifted to longer wavelengths. It may be expected that at higher fields, the recovery time could be further reduced to the order of 10ps on the basis of the results shown in figure 3.

2.5 Measurement of Carrier Emission Rates in Symmetric Barrier SQWs

To avoid the compexity of the carrier dynamics and the optical response of a multiple quantum well, a single quantum well structure was employed. A waveguide geometry was necessary because there is insufficient absorption perpendicular to the quantum well. The structure ws supplied by Dr A Moretti of Amoco Research Laboratory and consisted of a 80Å thick well and 30% aluminium barriers. The waveguide was a 0.5μm core 30% aluminium core with 40% aluminum upper and lower cladding regions. p-i-n doping allowed the application of an electric field across the structure and a 3μm wide rib provided transverse confinement. Excite pulses were TE polarized while probe pulses werer TM polarized the same as in the MQW case descibed above however with

nonlinear absorption was monitored instead of nonlinear refraction.

Depending on wavelength of probing, different effects could be observed in the transient reponse. These arise from a combination of exciton saturation (and broadening) and the dynamics of the quantum confined Stark effect due to field screening. The recovery times in the absense of an applied field were measured to be around 150ps, figure 12, (compared to 500ps in the multiple quantum well case). The conclusioon is that re-trapping into the wells is very significant for cross-well transport in the MQW case. On the other hand, once the carriers escape from the single quantum well, they do not contribute again to the optical nonlinearity thus giving a much faster response time.

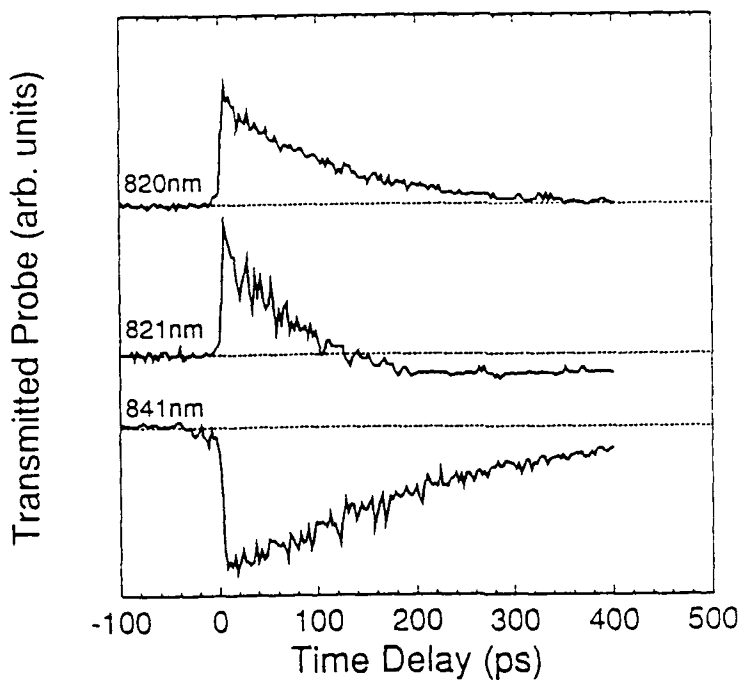

Figure 12 Change in transmission for the probe pulse as a function of time delay between the probe for three different laser wavelengths indicated. The sample had no external bias in these cases.

When electrically reverse-biased, the response time decreases to 20ps at a bias voltage of 20V. We have calculated the field dependent escape times due to thermionic emission and tunneling mechanisms, figure 13. The experimental results show general agreement with the thermionic emission model.

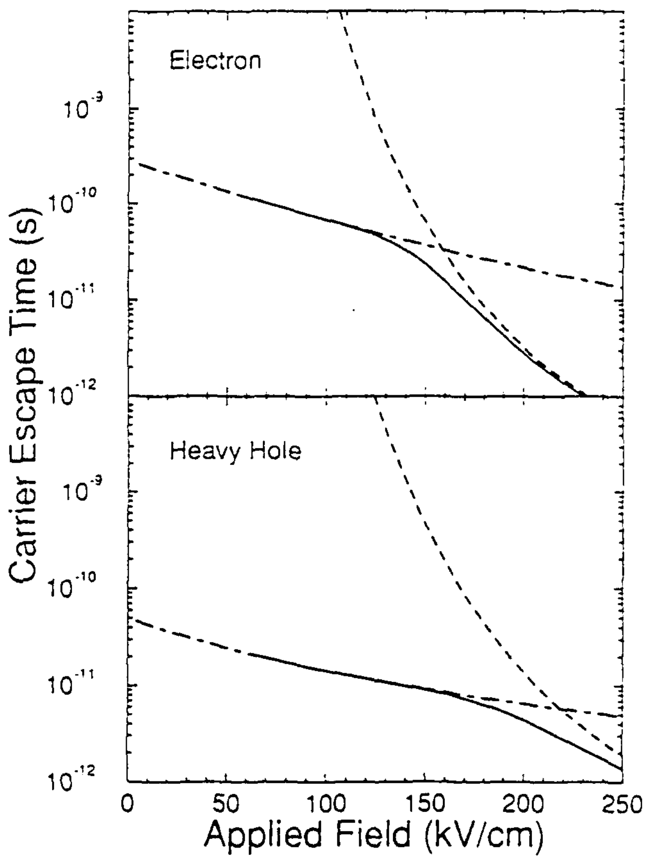

Figure 13 Calculated escape time from a single GaAs well of thickness 8nm surrounded by $Al_{0.3}Ga_{0.7}As$ barriers for electrons and heavy-holes as a function of electric field due to thermionic emission (Chained curve), tunneling (dashed curve) and the net effect of both (solid curve).

2.6 Simultaneous Measurement of Electron and Hole Emission in Asymmetric Barrier SQWs

Ridge waveguides were fabricated from samples grown at AT&T by MBE with a single GaAs/AlGaAs quantum well and asymmetric barriers, i.e. different aluminum concentration in the AlGaAs barrier layers on either side of the quantum well, in order to investigate the individual influence of the electrons and holes to the transient optical response. Two complementary samples were studied, figure 14, sample A had a low barrier on the side of the well nearest the n-doped region in order to reduce electron escape time while a second sample B had a low barrier on the side of the well nearest the p-doped region. A temperature dependence study is currently being carried out in order to verify thermionic emission models for quantum wells.

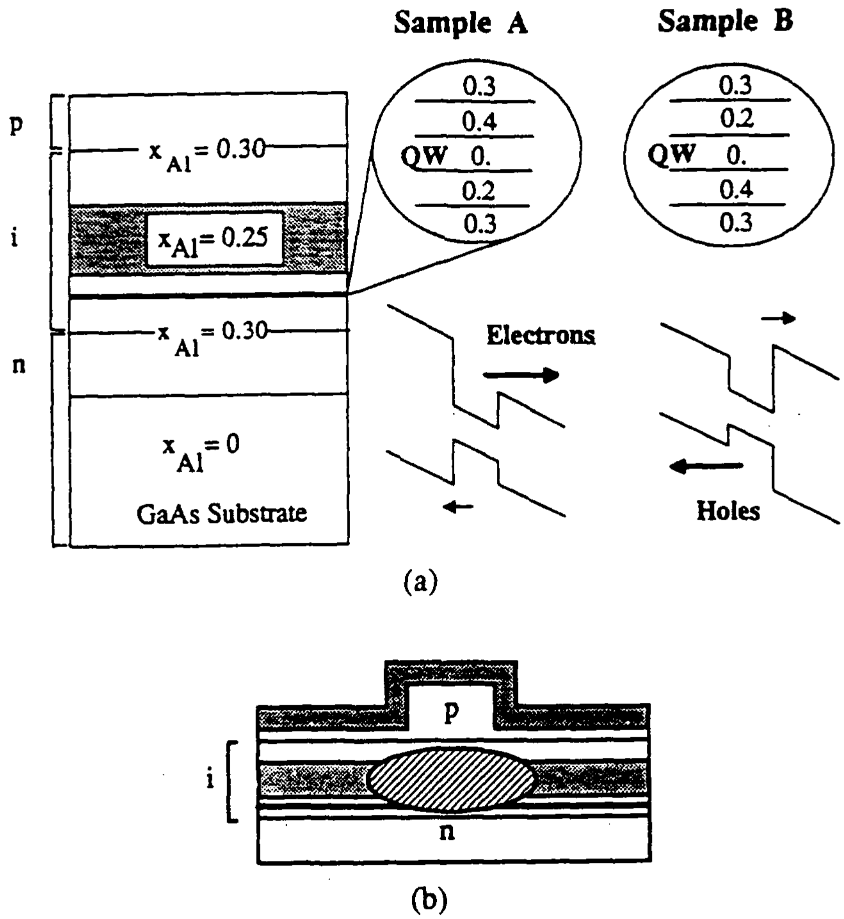

Figure 14 Schematic structure of asymmetric barrier single quantum well waveguides showing complementary structures A and B.

Experiments were carried out in a similar fashion to the waveguide measurements already described above. The shape of the temporal response is a sensitive function of both applied field and probe wavelength, figure 15. The temporal change in transmission is modeled as a sum of contributions from the QCSE and the recovery of the exciton saturation. The time dependence of the electric field in the quantum well is calculated using an analytical model involving both electron and hole escape times. For small changes in the electric field the QCSE is assumed to be proportional to the field change. Exciton saturation is modeled as an instantaneous rise in transmission followed by exponential decay dependent on an electron escape time constant. Fitting this model to experimental measurements allows for the discrimination between electron and hole contributions for the different barrier heights as a function of voltage, figure 16. The measured hole emission rates differ significantly from those predicted by presently accepted models of thermionic emission and will be the subject of further study because of the importance of these parameters to a number of quantum well optoelectronic devices.

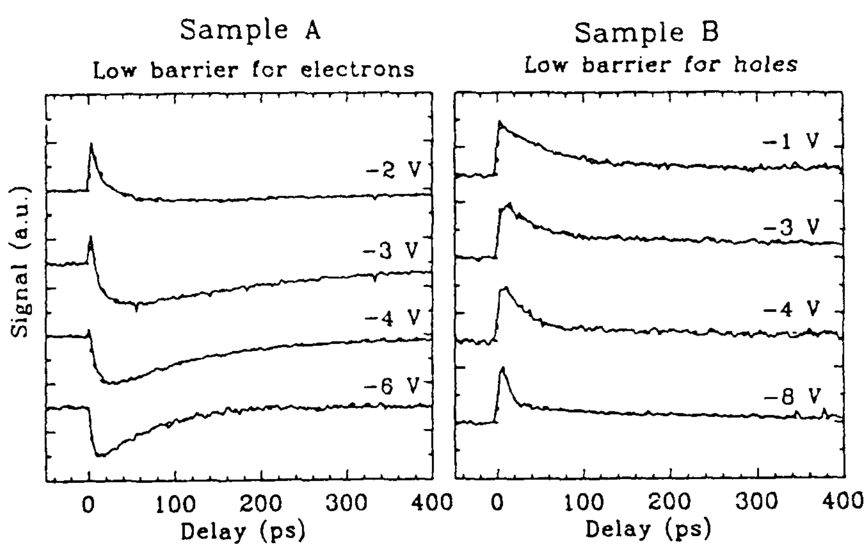

Figure 15 Relative changes in probe transmission induced by the pump as a function of time for samples A and B. Dotted lines are theoretical fits.

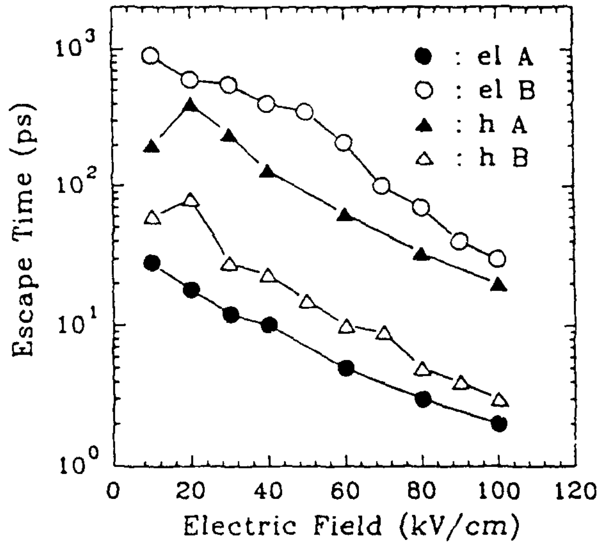

Figure 16 Electron (circles) and hole (triangles) escape times for sample A (filled symbols) and B (open symbols), as a function of applied electric field.

By varying the temperature we have observed that the time constants for both electrons and holes decay exponentially with increasing temperature, figure 16. The time constants changed by a factor of ~2 over a 50 degree temperature change. This provides direct evidence that the emission is thermionic as previously hypothesized.

2.7 Spin Relaxation, Phase-Space Filling and Carrier Transport

We have used picosecond excite-probe measurements of electron spin dynamics in a unique experiment to reveal that phase space filling and Coulomb screening contribute almost equally to excitonic saturation. To our knowledge this is the first measurement which has been able to distinguish between these two contributions which have a number of device implications.

Time resolved measurements of optical orientation determined a room temperature spin

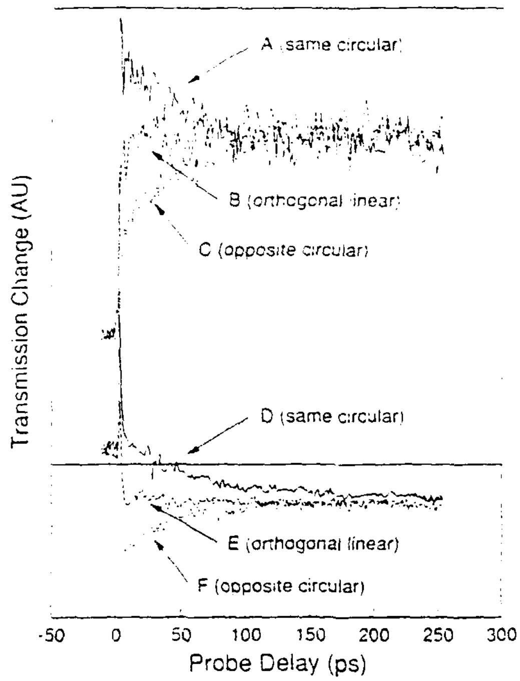

Figure 17 Excite-probe scans for a variety of beam polarizations. Curve A through C were performed at heavy hole resonance while curves D through F were taken on the low energy side of the exciton. A 60ps spin relaxation time is evident for these 6.5nm wells at 300K.

relaxation time in an undoped 6.5nm well thickness, GaAs/AlGaAs multiple quantum well sample. The laser wavelength was tuned to the peak of the heavy-hole exciton. Completely spin-polarized electron and hole distributions are possible in MQWs because the degeneracy of light and heavy hole bands is lifted since transitions from the heavy hole band can be is isolated from the light hole transitions. Excitation by right or left circularly polarized light results in the promotion of either $m_j = 1/2$ or $m_j = -1/2$ electrons to the conduction band, quantized with respect to the direction of laser light propagation. On the other hand, linearly polarized beams produce equal amounts of spin-up and spin-down electrons. Saturation of the exciton absorption is caused by both Coulomb

screening and phase space filling (psf). However, saturation of excitons by psf can only occur due to electrons with like spin. Figure 17 shows time resolved measurements for different combinations of optical polarizations at the peak of the exciton absorption and on the wavelength side where broadening becomes important. The difference in each set of signals is due to the difference in psf for the different spin polarizations. The result for linear polarization gives both Coulomb and psf contributions. We can thus deduce that psf is of the same magnitude as the Coulomb contribution and the spin relaxation time is 60ps.

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3. List of Publications and Presentations

"Modeling of cross-well carrier transport in a multiple quantum well pin modulator"
D.C. Hutchings, C.B. Park and A Miller *Appl. Phys. Lett* 59 3009-3011 (1991)

"Time resolved measurements of cross-well transport in a MQW pin modulator at high photogenerated carrier densities"
A. Miller, C.B. Park and P. LiKamWa *Appl. Phys. Lett.* 60 97 (1992)

"Simultaneous measurement of electron and hole escape times from biased quantum wells"
J.A. Cavailles, D.A.B. Miller, J.E. Cunningham, P. LiKamWa and A. Miller *Appl. Phys. Lett.* 61 (4) 426-8 (July 1992)

"Simultaneous measurement of electron and hole sweep-out from quantum wells and photoinduced field screening dynamics"
J A Cavailles, D A B Miller, J E Cunningham, P LiKamWa and A Miller *IEEE J Quantum Electron.* 27 (10) 2486-2497 (Oct 1992)

"Optical nonlinearities in GaAs-GaAlAs multiple quantum-well hetero-nipi waveguides"
C. Thirstrup, P.N. Robson, P. LiKamWa, M.A. Pate, C.C. Button, J.S. Roberts, *IEEE J. Quant. Electron.* QE-28 864 (1992)

"Laser-induced ultrasonic wave gratings in semiconductor thin fims"
J. Wang, D.C. Hutchings, A. Miller, E.W. Van Stryland, K.R. Welford, I.T. Muirhead and K.L. Lewis *J. Appl. Phys.* (accepted for publication)

"Excite-probe studies of carrier escape dynamics in a single quantum well waveguide"
R Bambha, D C Hutchings, M J Snelling, P LiKamWa, A Miller, A L Moretti, R W Wickman, K A Stair, T E Bird, J A Cavailles and D A B Miller, submitted to *Appl. Phys. Lett.*, Aug 1992

"Ultrafast charge transfer and optical switching in MQWs"
A Miller, P LiKamWa, D C Hutchings and C B Park *Proceedings of the US Army Workshop on Electro-Optical Materials*, Oct 1991, Huntsville, (GACIAC, Chicago, 1991) Vol PR 91-03, 151-165

"All-optical bistable switching with gain in an InGaAs/GaAs quantum well waveguide"
A Miller, P LiKamWa, M Ogawa, R M Park *Proceedings of the US Army Workshop on Electro-Optical Materials*, Oct 1991, Huntsville, (GACIAC, Chicago, 1991) Vol PR 91-03, 167-173

"Modeling of cross-well carrier transport in a multiple quantum well pin structure"
D Hutchings, C B Park, A Miller *OSA Annual Meeting*, San Jose, Nov 1991

Invited: "Optical switching and transient carrier transport phenomena in MQW structures"
A Miller, P LiKamWa, C B Park, D C Hutchings, *SPIE OE-Lase* meeting, Technical conference proceedings, 1626, Los Angeles Jan 1992

"Ultrafast nonlinear transmission changes in a GaAs single quantum well waveguide structure suitable for ultrafast all-optical switches"
P LiKamWa, A Miller, R Bambha, A Cavailles, A L Moretti, R W Wickman, K A Stair, T E Bird, *Integrated Photonics Research*, New Orleans, April 1992

"All-optical switching using dispersive nonlinearities in InGaAs/GaAs single quantum well laser diodes"
P LiKamWa, T W Kao, A Miller, M Ogawa, R M Park, *Integrated Photonics Research*, New Orleans, April 1992

"All-optical bistable switching with gain in an InGaAs/GaAs quantum well waveguide"
T W Kao, P LiKamWa, A Miller, M Ogawa, R M Park, P Cooke SPIE's OE/Aerospace Sensing '92, *Advances in optical information processing*, April 1992

"Nonlinear switching in a regime of optical gain in InGaAs/GaAs singel quantum well waveguides",
P LiKamWa, T W Kao, A Miller, M Ogawa, R M Park, P Cooke *Conference on Lasers and Electro-Optics (CLEO)*, Anaheim, May 1992

"Ultrafast measurements of the nonlinear transmission changes in a GaAs single quantum well waveguide structure with potential application for all-optical switches"
P LiKamWa, A Miller, R Bambha, A Cavailles, A L Moretti, R W Wickman, K A Stair, T E Bird, *Conference on Lasers and Electro-Optics (CLEO)*, Anaheim, May 1992

"Cross-well transport of photo-generated carriers in heterostructures"
D C Hutchings, A Miller, *Quantum Electronics and Laser Science (QELS)*, Anaheim, May 1992

"Time resolved studies of optical nonlinearities in single asymmetric quantum well p-i-n waveguides"
J A Cavailles, D A B Miller, J Cunningham, P LiKamWa, A Miller, *XVIII International Quantum Electronics Conference (IQEC)*, Vienna, June 1992

Invited: "Transient carrier transport phenomena and optical switching in MQW structures"
A Miller *Eighth interdisciplinary laser science conference (ILS-VIII)*, Albuquerque, Sept 1992

4. **List of scientific personnel**

Dr Patrick LiKamWa	Research Scientist and Adjuct Assistant Professor of Electrical Engineering
Dr Michael Snelling	NATO Visiting Research Fellow
Dr C B Park	Research student - Ph.D. (EE) gained May 1992
Ms H S Wang	Research Student - M.S. (Physics) gained May 1992)
Ms M Perozzo	Research student - workig towards a Ph.D. in physics
Mr R Bambha	Research student - working towards a M.S. in EE

5. **Interactions and Collaborations**

Joint experiments have been continued with Dr D A B Miller's group at AT&T Holmdel. Patrick LiKamWa spent one month working at AT&T, fabricating waveguide structures and carrying out time resolved measurements on carrier sweep-out times on structures grown by MBE at AT&T. These measurements are continuing in the same samples at CREOL where the intention is to make a thorough investigation of thermionic emission mechanisms from the quantum wells.

We have collaborated with Dr Tony Moretti, Amoco Research Laboratory on single quantum well, symmetric barrier waveguide structures. A number of waveguide structures have been supplied for studies of carrier emission rates from single wells. We have successfully demonstrated a significantly faster carrier sweep-out time in a single quantum well device compared to multiple well structures.

Collaboration with Dr Mitra Dutta at ETDL, Fort Monmouth involves supply and joint characterization of MQW samples grown by MBE at ETDL. An additional developing collaboration is with Dr Paul Cooke at ETDL on ultrafast characterization studies of strained layer InGaAs/GaAs lasers. On a parallel project, intermixed quantum well samples are being characterized by SIMS

analysis at Charles Evans Associates in collaboration with Dr Robert Wilson at Hughes Malibu and Dr John Zavada, Army Research Office.

We have received a number of MQW pin modulator samples from Dr Gareth Parry at University College London for the purpose of studying the modification of transient phenomena on partially intermixed MQWs. Controlled post-growth modifications to MQW structures could have the effect of increasing the switching speed of directional couplers, the modulation rate of SEED-type devices and the high frequency operation of QW semiconductor lasers.

Dr Robert Park, University of Florida has continued to supply MQW samples for intermixing studies and single quantum well InGaAs/GaAs lasers for studies of optical switching with gain.